

DISCOVERY OF THE LOW-ENERGY CUTOFF IN A POWERFUL GIANT RADIO GALAXY

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ABSTRACT

The lobes of radio galaxies and quasars, fed by jets and hotspots, represent a significant, and currently ill-constrained, source of energy input into the inter-galactic medium (IGM). How much energy is input into the IGM depends on the *minimum* energy to which the power-law distribution of relativistic particles is accelerated in the hotspots. This has hitherto been unknown to within three orders of magnitude. We present direct evidence for the discovery of this low-energy cutoff in the lobe of a Mpc-sized radio galaxy via the existence of extended X-ray emission, inverse-Compton scattered from *aged* radio plasma, and its separation by 80 kpc from regions containing *freshly accelerated* plasma from the hotspot. The low-energy cutoff of $\gamma \sim 10^4$ in the hotspot is higher than previously thought, but reconciles discrepancies with magnetic field estimates which had been systematically lower than equipartition values. The inverse Compton scattering of the spent synchrotron plasma is at the expense of cosmic microwave background (CMB) photons; we comment on the importance of such giant radio galaxies as contaminants of CMB anisotropies.

Subject headings: Galaxies: jets, radio galaxies: individual: 6C0905+3955, 4C39.24

1. INTRODUCTION

Knowledge of the energy input into the IGM from a powerful radio galaxy is necessary to understand the feedback of radio jets and lobes on their environments and hence their influence on cosmic structure formation. Estimates of this energy have been used to attempt (Wardle et al 1998; Celotti et al 1998; Celotti 2003) to discriminate between whether the constituents of jet plasma are electron-positron (light jets) or electron-proton (heavy jets), which has considerable implications for the jet-production mechanism at the supermassive black holes from which the jets emanate. To calculate the energy stored in the radio lobes, it is necessary to integrate over the entire energy distribution of the particles in the plasma which constitutes the lobes. The spectral shape, constrained by observations, is often a good approximation to a power-law meaning that there are very few high Lorentz factor (γ) particles and many orders of magnitude more low- γ particles. The lower limit of this energy distribution, hereafter γ_{\min} , was hitherto barely constrained by observations or theory (Carilli et al 1991; Hardcastle, Birkinshaw & Worrall 2001) and is thus crucial for even an approximate estimate of the energies involved. A considerable range of values for γ_{\min} is covered by different authors who are forced to make an arbitrary assumption (e.g. $\gamma_{\min} = 1$ is used by Hardcastle (2005) and also by Kaiser et al. (1997), $\gamma_{\min} = 10$ is used by Croston et al (2005), $\gamma_{\min} = 100$ is used by Carilli et al (1991), 1000 is taken by Wardle et al (1998)). This important point is actually rather obscured by the fact that many authors state an assumed minimum frequency ν rather than a minimum γ , following Miley (1980).

2. COMPARISON OF X-RAY AND RADIO EMISSION

The *Chandra* X-ray satellite is revolutionizing studies of radio galaxies and quasars since it is now possible to resolve extended X-ray emission from hotspots, jets and lobes. An extremely useful web-site documents discoveries to date.⁴ While studies of jets and hotspots in these objects reveal much about speeds and magnetic fields, our focus in this paper is on the radiation from the lobe regions (i.e. plasma that has been output from the hotspot). We proposed for *Chandra* observations of some giant radio galaxies as part of a study to investigate the population of relativistic particles in their lobes having *lower* Lorentz factors than can be probed by radio observations of synchrotron emission. In all standard models of radio source evolution (Baldwin 1982; Kaiser et al. 1997; Blundell, Rawlings & Willott 1999) longer (i.e. more extended) sources are older than shorter sources; as such, giant radio galaxies should be expected to have older plasma (having lower Lorentz factors than freshly accelerated plasma which has suffered less losses) than shorter sources.

A particularly important target amongst these is the powerful classical double (FRII Fanaroff & Riley 1974) radio galaxy 6C 0905+3955 (also known as 4C39.24), at the relatively high-redshift of $z = 1.88$ (Law-Green et al 1995). This object has a physical size projected on the plane of the sky of 945 kpc [using the assumed cosmology of $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$ and its measured angular size of $111''$].

The radio emission from 6C 0905+3955, shown in Figure 1, and indeed at 408 MHz in figure 1a of Law-Green et al (1995) which closely resembles our image at 1.4 GHz, represents the entirety of the radio emission at these frequencies: the radio lobes seen just inward of the compact hotspots, together with the core, have the same silhou-

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ette at low frequency (Law-Green et al 1995) as our high frequency image in Figure 1 shows. The 408-MHz MERLIN image of Law-Green et al (1995) demonstrably does not undersample much smooth extended emission because the total flux density measured from the MERLIN 408-MHz image is the same as the measured total flux density of 940 mJy measured by the Bologna 408-MHz survey (Ficarra, Grueff & Tomassetti 1985) which measures integrated flux density. Moreover, comparison of the integrated flux density from our 1.4-GHz image (266 ± 3 mJy) and that from the NVSS observations (260 ± 4 mJy) by Condon et al (1998) is consistent with no radio flux density having been lost because of interferometric undersampling in the extended VLA configurations.

The *Chandra* X-ray satellite observed 6C 0905+3955 on 2005 March 02: the X-ray emission from this object is well-detected in 19.68 ks with about 114 cts in total (all counts quoted are background subtracted), and is spread in a linear fashion contained within the giant radio structure (Figure 1). The (background subtracted) counts are divided between: the lobe which contains 81 cts and the nucleus which contains 11 cts, a region with 15 cts associated with the western radio hotspot and a region containing 9 cts which is towards the eastern radio hotspot, but actually 80 kpc from it in the direction of the nucleus. There is no indication of any host cluster or group in the relatively short exposure.

Inspection of images in different energy bands indicates that the nucleus or core is hard and the remainder (i.e. the emission from between the hotspots but excluding the nucleus) is soft. Despite the low count rates, crude spectra are extracted and summarised in Table 1.

The unsmoothed image (upper panel, Fig 1) shows that the X-ray emission just to the east of the core is resolved transversely with a width of ~ 40 kpc, larger than the transverse width of the radio lobe seen rather further to the East, and is thus most un-jet-like. The X-ray emission does not in any way resemble the fine and slender collimated jet emission which has been observed in FR I radio sources and low-redshift FR II sources⁵ and so strongly suggests that this X-ray emission arises from the same plasma that at earlier times would have been radio-emitting lobe material.

Comparison of the X-ray and radio structures seen in Figure 1 shows that the vast majority of the X-ray emission seems to be associated with the regions *inside* the radio lobes rather than spatially coincident with them (leaving aside the nucleus where different physics is at play). These regions are where the hotspots would have *previously* passed through, depositing then freshly accelerated plasma, on their journey outward from the central nucleus of the active galaxy. This plasma would have radiated synchrotron emission for at most a few 10^7 years at observable radio wavelengths (Blundell & Rawlings 2000), and is subject to energy losses from four principal means (Blundell, Rawlings & Willott 1999): i) adiabatic expansion losses as the plasma escapes from the high pressure hotspot into the lower pressure lobe, ii) adiabatic expansion losses as the over-pressured lobe itself expands into the IGM, iii) synchrotron losses and iv) inverse Compton losses off the CMB. Simple calculations show that (i) means that the

Lorentz factors of all particles will reduce by a factor of typically ten (Scheuer & Williams 1968; Blundell, Rawlings & Willott 1999) after exiting the compact hotspot and expanding into the lobe and (ii) means there will be a continuous reduction in their Lorentz factors by an amount which depends on the subsequent fractional increase in volume of the lobe. [Note that (iii) and (iv) make only a slight difference to the low- γ particles since these losses depend on γ^2 .] Thus, whatever is the minimum Lorentz factor (γ_{\min}) resulting from acceleration in the hotspot, it will give rise to a γ_{\min} which is at least an order of magnitude lower in the lobes — we now establish what these values of γ_{\min} are in these two locations.

3. RELEVANT LORENTZ FACTORS

To suggest that the X-ray emission seen to the east of the nucleus is synchrotron emission, in a region where there is negligible radio emission even at 408 MHz (see previous section) would require an unprecedented spectrum of relativistic particles having significant number density with Lorentz factors of 10^7 and rather less with 10^4 , which would require an unprecedented acceleration mechanism; therefore, it is assumed that there is no particle acceleration taking place to cause this. A much more conservative explanation is the process of inverse-Compton scattering of CMB photons (ICCMB) by relativistic electrons widely believed to be in the lobes of radio galaxies, which we now explore. The usual assumption is made throughout that the plasma which comprises the lobe (or what used to radiate at radio wavelengths as lobe material) is not moving relativistically, so investigation of beamed ICCMB would be inappropriate here.

Synchrotron particles with Lorentz factor γ will upscatter CMB photons (ν_{CMB}) to higher frequencies (ν_{X}) according to:

$$\frac{\nu_{\text{X}}}{\nu_{\text{CMB}}} = \left(\frac{4}{3}\right) \gamma^2 - \frac{1}{3}. \quad (1)$$

On the assumption that it is the photons from the peak of the CMB distribution which are inverse Compton upscattered by the spent synchrotron plasma in the lobes, then the Lorentz factors responsible for the emission observed at 1 keV are 1.5×10^3 , so the presence of ICCMB mandates the existence of $\gamma \sim 10^3$ particles in the lobe region. Note that these particles will have suffered considerable adiabatic expansion losses on leaving the hotspot, but these preserve the shape of the spectrum. The steep power-law spectrum (if did continue to low energies) would predict many more $\gamma \sim 10^3$ particles in the hotspot than in the lobe, however, the absence of X-ray emission and thus ICCMB in the east (left) hotspot mandates the absence of $\gamma \sim 10^3$ particles there, i.e. the particle spectrum in the hotspot cuts off above these low energies. If we conservatively take γ_{\min} in the lobe to be $\sim 10^3$ then this requires the lower limit to the γ_{\min} in the compact east hotspot to be $\sim 10^4$.

The X-rays are much more pronounced in the regions of the lobes containing spent, rather than currently radiant, synchrotron plasma. The extended X-ray emission is therefore most likely produced by non-thermal particles which no longer contribute to the observed radio emission.

⁵ <http://hea-www.harvard.edu/XJET/>

In fact, the X-ray emission only seems to appear where the east radio lobe has undergone significant transverse expansion (at Right Ascension 09 08 21.5, see Figure 1); closer to the central engine still, the lobe plasma has presumably undergone still further transverse expansion so that its magnetic field strength is too low there to cause the remaining low Lorentz factor particles to radiate at radio wavelengths. However, by Equation 1, the X-ray emission traces the location of old synchrotron particles, injected by the hotspot a long time ago, whose energies are now reduced down to a Lorentz factor $\gamma_{\min} \sim 10^3$. The lobe radio emission observed at 408 MHz (Law-Green et al 1995) adjacent to the compact hotspots will require rather higher Lorentz factors than this value of γ_{\min} (assuming magnetic field strengths $\lesssim 1$ nT) as the particles recently accelerated in the hotspots and then released into the lobes emit synchrotron radiation in the magnetic fields there. So whilst electrons with such low Lorentz factors in the more aged regions of the lobes cannot produce synchrotron radiation at observable radio frequencies, they are ideally matched to upscatter CMB photons into the *Chandra* X-ray energy bands.

The radio/X-ray comparison in Figure 1 shows a separation of the outermost X-ray emission from the outermost radio emission towards the east, by ~ 80 kpc. This is the first direct indication of the elusive low-energy cutoff for plasma energized in hotspots, as it implies that there are no such low-energy particles in plasma recently accelerated in the hotspots. This has implications for the physical mechanism for particle acceleration in hotspots: for example, it may be that the only particles to escape from hotspots into lobes are those with gyro-radii larger than the shock front, while less energetic particles with smaller gyro-radii are very rapidly accelerated within the thickness of the shock (which is of course on size-scales much smaller than current observations of hotspots resolve).

The western hotspot of 6C 0905+3955 appears to be an exception to this behaviour, in that there is very approximate spatial correspondence between the X-ray and radio emission (see inset to Figure 1). It could be that in this side of the source, X-ray emission is seen much closer to the radio hotspots because expansion losses are so much greater in their vicinity (note the transverse size of the west lobe is rather larger than that of the east lobe) and lower- γ particles are therefore expected to be present much closer to this hotspot. It is also possible that different physics is responsible for this emission: for example, synchrotron self-Compton as in the hotspots of Cygnus A (Wilson, Young & Shopbell 2001), or perhaps X-ray emission from a galaxy responsible for the putative gravitational lensing of this hotspot (Law-Green et al 1995).

4. IMPLICATIONS OF A HIGH γ_{\min}

If the γ_{\min} of the particles accelerated in the hotspots is *higher* than has previously been thought, the equipartition magnetic field strength, B_{eq} (calculated on the basis of the observed luminosity and the assumption that in the lobes there is equal energy stored in the magnetic fields as in the relativistic particles), will be *lower* than previously thought. The relationship between γ_{\min} and B_{eq} is given

by:

$$B_{\text{eq}} \propto \left(\frac{1}{\gamma_{\min}} \right)^{\frac{2\alpha-1}{3+\alpha}} \quad (2)$$

where α is the frequency spectral index of the flux density $S_\nu \propto \nu^{-\alpha}$ at frequency ν . Thus, if γ_{\min} of the lobes is assumed to be 10 (or 100), but is in reality 10^3 , then the inferred B-field is discrepantly larger than the true value by 4 (or 2). These are approximately the factors by which estimated equipartition field strengths, calculated assuming the lower values of γ_{\min} , are larger than independently estimated B-fields from co-spatial inverse-Compton X-ray and synchrotron radio emission (Brunetti et al 2002; Harris & Krawczynski 2002; Kataoka et al 2003; Croston et al 2005). Thus, knowledge that γ_{\min} is higher than previously assumed may well reconcile these discrepant values.

If lobe magnetic field strengths are *lower* than previously assumed, a corollary is that a higher normalisation of the particle energy spectrum is required to produce a given observed synchrotron luminosity. The number density normalisation N_0 of synchrotron particles for a power-law distribution of particles depends on γ_{\min} as follows:

$$N_0 \propto \gamma_{\min}^{\frac{(2\alpha-1)(1+\alpha)}{(3+\alpha)}}, \quad (3)$$

where α is the frequency spectral index measured to be $\alpha = 1.1$ in 6C 0905+3955, giving $N_0 \propto \gamma_{\min}^{0.6}$ in this object. The total number density n_{rel} is given by $n_{\text{rel}} = N_0/[2\alpha\gamma_{\min}^{2\alpha}]$.

5. IMPLICATIONS FOR THE RELATIVISTIC SUNYAEV-ZELDOVICH EFFECT

The dependence of number density of particles on γ_{\min} has implications for the relativistic Sunyaev-Zeldovich effect (Sunyaev & Zeldovich 1969; Zeldovich & Sunyaev 1970; Birkinshaw 1999) from the plasma lobes of radio galaxies. The optical depth of relativistic electrons is given (Ensslin & Kaiser 2000) by

$$\tau_{\text{rel}} = \sigma_T \int d\ell n_{\text{rel}}, \quad (4)$$

where σ_T is the Thomson scattering cross-section and ℓ is the line-of-sight distance through the lobe (taken to be 3 arcsec which is 25 kpc in the assumed cosmology) and n_{rel} is the number density of relativistic particles (obtained by integrating over N_0 in Equation 3, as stated at the end of Section 4). The fraction of photons upscattered from the CMB via the relativistic Sunyaev-Zeldovich effect is given by τ_{rel} — this upscattering is assumed to be at the wavelength of the peak of the CMB photon distribution which at $z = 1.88$ is 3.7 mm, corresponding to a frequency of 82 GHz. 6C 0905+3955 is the target of future observations to verify the value of γ_{\min} found in this Letter to search for a decrement of intensity in this frequency regime.

Taking a value of 10^3 for the value of γ_{\min} in the lobes gives a value of $\tau_{\text{rel}} \sim 10^{-10}$ for the radio emitting regions. The value of τ will obviously be increased above this value in the regions where X-rays are observed. If such values of γ_{\min} are typical (for $\alpha > 0.5$) then radio galaxies are unlikely to be as important for CMB decrements as suggested by Ensslin & Kaiser (2000), unless the equipartition paradigm does not in general hold in these objects.

Future experiments should be sensitive to such levels of contribution to CMB decrements on the angular

sizes probed by giant (or relic) radio galaxies such as 6C 0905+3955 and, in combination with future Chandra imaging, deepen our understanding of the physical conditions in these objects.

6. SUMMARY

The extended structures of the giant radio galaxy 6C 0905+3955 in X-rays and radio have been compared and show that the bulk of the X-ray emission associated with non-compact components (i.e. lobe material) preferentially occurs where the synchrotron plasma is expected to be oldest. Since X-ray emission from ICCMB comes from electrons with Lorentz factor $\gamma \sim 10^3$, this strongly suggests that there is an increased presence of $\gamma \sim 10^3$ particles in the older plasma than in the more recently accelerated plasma.

If the equipartition paradigm is valid then, $\gamma_{\min} \gtrsim 10^3$ if generally true means that the equipartition magnetic field strengths are lower than previously assumed. The value of γ_{\min} affects the optical depth of the relativistic electrons in the radio lobes; it is important to establish the generality of our discovery in order to be sure about the importance of the relativistic Sunyaev-Zeldovich effect from radio galaxy lobes imprinted in the details of the CMB.

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Region	Total counts (background)	Γ	L_X (2 : 10 keV) $10^{44} \text{ erg s}^{-1}$
nucleus	11 (0.14)	2	1.2
lobe	81 (27.19)	$2.7^{+0.7}_{-0.7}$	2.1
		2	2.8
western-most X-rays	15 (2.4)	$2.5^{+0.7}_{-0.6}$	0.6
		2	0.7
eastern-most X-rays	9 (1.57)	$1.4^{+1.0}_{-0.3}$	0.5
		2	0.4

TABLE 1

THE PHOTON NUMBERS FOR DETECTION PURPOSES ARE FROM THE 0.3 TO 3 keV BAND WHILE THE SPECTRAL FITS WERE MADE OVER THE FULL 0.5 TO 7 keV BAND. FOR THE EASTERN-MOST X-RAY EMITTING REGION, WHICH IS SOME 80 KPC FROM THE EAST RADIO HOTSPOT, THE PROBABILITY OF DETECTING 9 PHOTONS WHEN 1.57 IS EXPECTED IS 3.9×10^{-5} , SO ITS DETECTION IS VERY SECURE. C-STATISTICS WERE USED TO CALCULATE THE X-RAY PHOTON INDEX, Γ , AND THE X-RAY LUMINOSITY IN THE REST-FRAME 2 – 10 keV-BAND, L_X . THE FIRST, THIRD, FIFTH AND SEVENTH LINES IN THE TABLE LIST THE LUMINOSITY CALCULATED FOR A FIXED PHOTON INDEX OF 2.

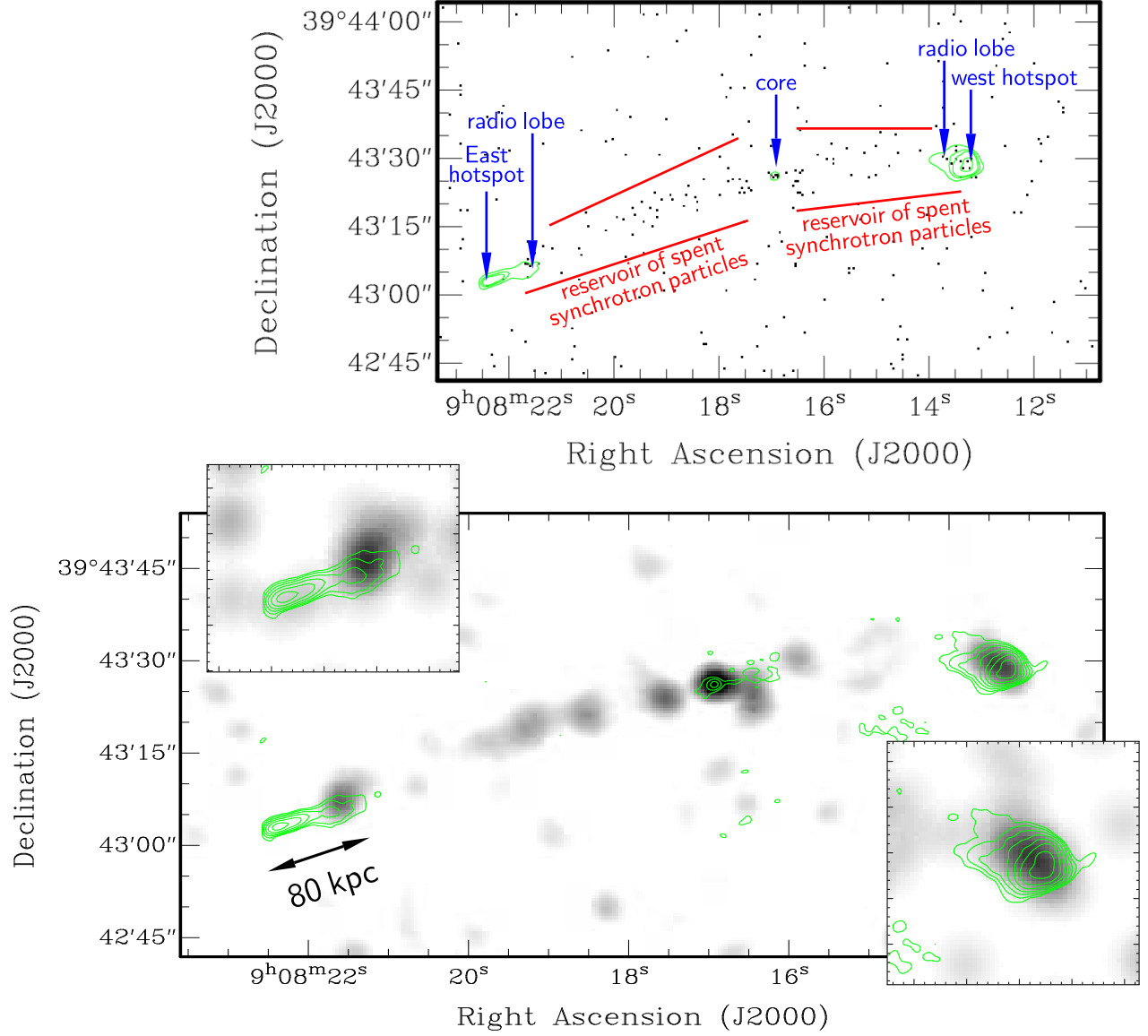


FIG. 1.— Upper panel: greyscale is unsmoothed X-ray (0.3-3 keV) emission from the giant radio galaxy 6C 0905+3955; green contours are of radio emission at 1.4 GHz from archival observations with the A-, B- and C-configurations of the VLA (the lowest contour is 0.6 mJy/beam). Blue labels indicate the nomenclature used for the radio emitting parts of the source and pairs of red lines indicate regions containing spent synchrotron lobe material having Lorentz factor particles that are too low to radiate at radio wavelengths but sufficient to inverse Compton scatter CMB photons to X-ray energies. Lower panel: greyscale, as upper panel, but smoothed by a four-pixel Gaussian; contours of the same radio emission at 1.4 GHz (the lowest contour is 0.4 mJy/beam).